# Injection-Molding

Oniszczuk, Tomasz; Janssen, Leon P.B.M.

*Published in:*
Thermoplastic Starch: A Green Material for Various Industries

# 10
# Injection-Molding

*Tomasz Oniszczuk, Leon P.B.M. Janssen*

One of the principal methods for shaping synthetic polymers is injection-molding. The thermoplastic is melted in a cylinder or in a screw device and is subsequently pressed into a cavity with a specific shape. After that, cooling and solidification occur under sustained pressure to compensate for shrinkage of the material, and after complete solidification the object can be ejected [1] (Figure 10.1). Important factors in the injection-molding process are the temperature of the material upon injection and the temperature of the mold. Temperatures that are too high increase the cycle time and therefore they decrease the process efficiency, whereas temperatures that are too low result in a so called short shot, when the material solidifies before the mold is completely filled. A second important factor is the so called "clamp force", which indicates the maximum force that can be exerted on the mold before it starts leaking. This clamp force in turn, together with the area of the cavity in the mold, determines the maximum injection pressure that can be used. The injection technique enables objects varying from grams to kilograms to be obtained. Subject to the plasticizing system, injection-molding machines are divided into two types:

- ***Ram injection,*** in which a piston pushes the material into the mold. This machine is only used for relatively simple and small objects. Melting in the cylinder is often the time-limiting factor.
- ***Screw injection,*** in which a small extruder produces the melt, while the screw moves backwards and the melt collects before the screw. Once enough melt has been collected the screw moves forward, pushing the melt into the cavity. Because of its faster melting process and better mixing this type of machine is used for bigger or more complicated objects and if a high cycle time is required.

The brothers J.W. and J.S. Hyatt in the USA patented the first piston injection mold press in 1872, when they solved the problem of plasticizing a mixture of nitrocellulose and camphor. Much later a screw-injecting molding machine was designed. Nowadays screw injection molding is the most commonly used method for thermoplastic materials.

*Thermoplastic Starch.* Edited by Leon P.B.M. Janssen and Leszek Moscicki

ISBN: 978-3-527-32528-3

**Figure 10.1** Injection-molding machine (ARBURG 220H90-350).

In Poland, A. Smorawiński made a substantial contribution to the dissemination and development of injection-molding, publishing the first book on this subject [2, 3].

## 10.1 Screw Injection Molding

Unlike in normal extrusion, the screw can move in the axial direction. The material is extruded while the screw is rotating, and this causes the screw to be pushed far enough back that the space in front of the screw remains completely filled with the material. If enough material has collected in front of the screw, the screw is pushed forward by means of a hydraulic system, causing the material to be expelled. The molten material now enters into small ducts (called runners) and is let into the cavities through a narrowed section (the gate). The runners have to be big enough for the drop in pressure to be acceptable and for the material in the runners not to solidify before the injection is complete, and they also have to be small enough to assure that the amount of scrap material from the runners is minimal.

Three thermal effects can affect injection-molding:

- ***To obtain a short cycle time,*** the hot polymer is injected into a relatively cold mold. As a result, the polymer will already be starting to solidify on the wall of the mold while it is still being injected. This will cause an additional resistance to the flow. In extreme cases, the resistance to the flow may become so great that the mold will not fill completely. This is described as a "short shot".
- ***Because injection-molding is a cyclic process,*** temperature variations in the polymer flow and in the temperature of the mold may occur.
- ***Viscous dissipation in the runners*** may lead to a considerable increase in temperature in the polymer flow.

Injection-molding can be done under conditions of constant throughput or constant pressure. Most processes, however, are carried out with constant throughput while the pressure increases during filling of the mold. As a result of the cooling and solidification of the material in the cavity, shrinkage will occur. To ensure that the object being injection-molded has the right shape, it is kept under high secondary pressure during solidification, with the mold remaining filled as a result. After solidification of the material in the gate, the pressure can be released. At this point the pressure in the mold should be so high that compression of the material will compensate for further shrinking due to solidification. When the object has cooled down sufficiently, the mold can be opened and the object can be ejected. These three stages are termed filling, packing, and cooling, respectively. The time required for the cooling can (if the objects are thick-walled, for example) determine the cycle time. In that case it may be worth considering use of a number of different molds for simultaneous filling by a machine.

The advantage of injection-molding with constant throughput is that once the volume of the mass that is to be injected (the so-called shot volume) is known, the injection time is easy to calculate and is not a function of process parameters such as viscosity. A disadvantage of injection with a constant throughput is that the pressure in the mold can become so high that the closing mechanism is no longer sufficiently rigid, and the mold will buckle away. This will cause frayed edges along the injection-molded article. Injection-molding machines are often described in terms of the maximum shot volume, the maximum injection throughput, and the maximum closing force or clamp force of the mold.

## 10.2 Injection-Molding Parameters

For the process of injection-molding the major thermal process parameters are:

- injection temperature,
- injection pressure, and
- mold temperature.

Optimal values of these parameters are of great importance for the time between two consecutive injections, the so-called cycle time, which in turn determines the economic feasibility of the process.

The injection process temperature is the temperature (or sometimes a range of temperatures), at which the mass is plasticized to such a degree that it may easily be injected from the heating cylinder into the mold. The choice of this temperature can depend on several factors, such as the type of polymer, the size and shape of the injected object, the maximum attainable pressure, and the mold temperature. The plasticizing of the material takes place in an electrically heated cylinder, where a certain temperature profile of the wall can be imposed. This temperature range is generally determined experimentally for the type of material, the kind of product, and the type of the injection-molding machine [4].

The injection pressure ($p_w$) is the pressure generated by the screw or the ram in the heating cylinder and it should be sufficiently high to press the plasticized mass from the cylinder into the mold, to fill the cooled mold completely before the material solidifies. The maximum injection pressure is determined on the basis of the diameter ($D$) of screw or ram, an external diameter ($d$) of the hydraulic piston in the shove and retract system of the screw or ram, the pressure in the hydraulic system ($p_h$), and the friction force ($F$) at screw shove [3]:

$$p_w * \frac{\pi D^2}{4} + F = p_h \frac{\pi d^2}{4} \tag{10.1}$$

from which:

$$p_w = p_h \left(\frac{d}{D}\right)^2 * \frac{4F}{\pi D^2} \tag{10.2}$$

The friction forces can be redefined in terms of frictional pressure by:

$$\Delta p_F = \frac{4F}{\pi D^2} \tag{10.3}$$

$$p_w = p_h \left(\frac{d}{D}\right)^2 - \Delta p_F \tag{10.4}$$

During the filling process the pressure in the mold itself ($p_g$), called the inner pressure, equals the injection pressure ($p_w$) minus the pressure decreases in the cylinder ($\Delta p_c$) the injection nozzle ($\Delta p_d$), and the runners (injection channels, $\Delta p_k$), respectively [3]:

$$p_g = p_w - \Delta p_c - \Delta p_d - \Delta p_k \tag{10.5}$$

The pressure required to pack the cavities in the mold mainly depends on the temperature of the mass at the nozzle and on the temperature increase due to viscous dissipation. This dissipation is proportional to the viscosity and quadratically proportional to the injection speed. Increased temperatures and the resulting decreases in viscosity improve the flow into the cavities, thus decreasing filling time, but they increase the cooling time needed before the object has solidified sufficiently to be ejected. A balanced choice of melt temperature and mold temperature is important for optimal production. Determination of these parameters is generally done experimentally.

Injection-molding machines are generally characterized by two different parameters: the maximum injection volume and the clamp force. The maximum injection volume determines the maximum volume of the object or of several objects in a single mold. The maximum clamp force is defined as the maximum force available to keep the mold closed without occurrence of leaking at the contact areas where the mold closes.

At the end of the injection cycle, when the flow has stopped no friction losses occur and Equation 10.4 degenerates into $p_g = p_w$. Because the maximum clamp force ($F_K$) equals the pressure in the cavity ($p_g$) times the projected area ($A$) the maximum projected size of an object that can be made on a particular machine is determined by:

$$A_{max} = \frac{F_K}{p_W} = \frac{F_K}{p_h}\left(\frac{D}{d}\right)^2 \tag{10.6}$$

***Injection process cycle***: The injection-molding process is cyclic. This means that each process phase proceeds in definite, repeated periods of time. The cycle time is the time between closing of the mold at the beginning and the mold closing again after ejection of the object. This cycle time is mainly dependant on the efficiency of the plasticizing system of the injection machine and the cooling of the object before it can be ejected. For a given material these times are related to the structure of the object and its size; they vary usually between a few seconds and some minutes. This period of time comprises the times of each cycle phase. For maximum injection performance, the cycle time should be optimized [3].

***Mold temperature***: In the mold the final stage of the injection process – that is, the shape development and fixing through the cooling of the material – takes place. The coolant is generally water. The mold temperature ranges from 25–80 °C, subject to product requirements, material type, and shape of the cavity. The mold temperature can affect the product properties and appearance. Especially if the material can crystallize upon solidification, like various synthetic polymers, the mold temperature influences the nucleation and crystallization speed, which in turn have an impact on the physical properties of the end product. A second effect, dependent on the cooling speed, is the molecular relaxation of the material. During the injection process the molecules will be stretched and oriented, resulting in internal stresses in the material. Fast cooling will result in these stresses being "frozen in", and the deterioration of the mechanical properties of an object will be much faster than in cases in which the molecules have been able to relax and to lose their orientation because of slow cooling.

***The plasticizing performance*** is, as stated before, another important parameter characterizing the injection process. It is defined as the maximum mass flow ( ) through a special nozzle at the end of the plasticizing system into the open space at the optimal rotary speed of screw. For practical application this value is taken as a standard for processing polystyrene ($G_n$) and other materials are related to it. In this way, the plasticizing performance for thermoplastic starches (or for other polymers) can be expressed as:

$$\dot{G} = k_{p1} * \dot{G}_n \tag{10.7}$$

where $k_{pl}$ stands for a coefficient of relative plasticibility of material in relation to polystyrene. The $k_{pl}$ coefficient values are the results only of the thermal properties of the material, and so they may differ slightly between samples or varieties of the same material [3, 4].

## 10.3 Injection Technology Use and Development Trends

Although the injection-molding of thermoplastic starches is still in its first stages of development, injection-molding is one of the most common shaping methods for synthetic polymers. In everyday life we encounter various types of packages, ready-to-use products, and household equipment manufactured with this technology. The most pronounced examples of this trend can be found in the car industry.

Products made by conventional injection-molding include the combined rear lights produced by the injection of many colors simultaneously. In special injection processes, suction manifolds for combustion engines are produced with the shell-forming technique, which combines injection and linking. Further examples from cars are jetting films for front panels of electrical equipment and spraying of lacquered components of the car body. The process depicted above must proceed under monitored conditions of the surroundings, and it is not only spotless surfaces that matter. For many applications optical quality is important, which requires a perfectly clean alloy, absolutely free from any inclusions. Such examples include optical data carriers, reflector glass, car windows, mirrors, prisms, car body interiors, and medical and pharmaceutical products [19, 20].

Because many injection-molding processes involve mass production, the future of this technique is closely connected to the use of readily available raw materials [2]. Extensive research into the introduction of biodegradable materials for the production of various objects is being performed all over the world; one of the most promising areas is the production of packaging. In this area, biopolymers, mostly based on various starches blended with plasticizers and natural fibers, represent good alternatives to synthetic plastics. The production parameters and the optimal mixture compositions having been established, it can be expected that thermoplastic starches will compete successfully with the conventional plastics in many areas of packaging.

There are several areas in which techniques used for synthetic polymers could be extended to thermoplastic starches. Combinations of material to form a product can be used in co-molding, for instance. At present in the plastics industry, co-molding is used to obtain cores made from recycled materials and skins that consist of virgin plastics. This technique could be extended to TPS: a core made out of thermoplastic starch in combination with a thin protective outer layer made from a synthetic polymer can be envisioned. After the life cycle of the product the outer layer would break during composting and the core would become free for biodegradation. A second example is the addition of a gas to form a foamed object, which is very common both in plastics processing and in snack technology. Equally, ready-foamed packaging material could be produced by injection-molding.

## 10.4
## Reinforced Injection-Molding

In order to improve the physical properties of biopolymers or to reduce the price of a ready product, various types of fillers and carriers can be added. The fillers can affect the mechanical, physical, and chemical properties of a final product. Fillers can be divided by source or by morphology: by source we can distinguish between organic or inorganic fillers and by morphology between powdered, fibrous, and lamellar shape. They include emulsifiers, cellulose, plant fibers, bark, kaolin, pectin, etc. Extenders have a considerable influence on the technological properties of materials and these supplements enable the primary shrinkage of test bars to be reduced.

It is most logical to add equally degradable fillers to biodegradable thermoplastic starch. Natural fibers may be added to biopolymers at amounts of 1% or even up to 20–45%, depending on the kind of fibers used. The most common fibers have proven to be flax, hemp, coconut, jute, or cotton fibers. To achieve better adhesion between the fiber and the matrix material, the fibers are often modified in acid solutions or in acetone for degreasing and to produce structural changes in the fiber surface [5–9].

In the production of objects from synthetic plastics, two kind of fiber reinforcements can in general be found: short fibers and structured fibers. In short-fiber reinforcement, chopped fibers of 6 mm to 1 cm are mixed with the polymers and injected as a more or less homogeneous mass. In objects reinforced with structured fibers a woven or non-woven fiber mat is placed in the mold before the mass is injected. At present only the short-fiber reinforcement has an analogue in biopolymers.

For the injection-molding process the use of short-fiber-filled materials has some consequences:

- The fibers can increase the viscosity considerably, leading to higher injection pressures and larger temperature increases due to viscous dissipation.
- The runners should be straight without sharp bends to prevent the fibers from clogging up. Also, the gate design has to be modified.
- Because a slight obstruction has the tendency to filter out fibers and to form a tight clog, safety measures to prevent too-high pressure build-up have to be build in, especially in machines with constant throughput.
- Because many fibers show abrasive action, molds for reinforced injection-molding should generally have higher hardness to prevent excessive wear.

## 10.5
## Application of Natural Fibers in Processing of Biopolymers

Natural fibers were already being used as reinforcement materials in ancient Egypt. House walls there used a mixture of clay, sand, and chopped straw, which

after being dried provided the first construction composite material [7]. More recently, many materials for manufacturing have contained various fibers. Obvious examples are textiles, linen, and paper, made from commonly available fibers such as hemp, cotton, and jute. Some of these fibers have been successfully applied ever since. It was as early as in 1986 that the first aircraft tanks and seats were made from a compound of synthetic resin and natural fibers.

Concerns about our natural environment, protection of natural resources, and the opportunity to re-use old packaging all contribute to the growing interest in environmentally friendly materials obtained from renewable sources. At present, we are witnessing a dynamic increase in the use of natural fibers in the processing of thermoplastic polymers. Elevated pro-ecological awareness and new legal regulations have caused a turnabout in the design of composite products in which traditional fibers were being replaced by artificial ones [10–12].

The application of composites containing natural fibers depends on the production cost of off-the-shelf articles and their functional properties. Natural fibers are claimed to be more cost-effective than fibers traditionally used for the production of composites, such as carbon fiber or glass fiber, in terms of their procurement and also to have lower density, high hardness, coherence, acceptable rigidity, and mechanical properties, to be easy machined, and, first and foremost, to be biodegradable [6, 9].

It is necessary to maintain a balance between economy and ecology. This results in the application of biocomposites in some specific areas, such as the automotive industry, furniture, construction materials, and packaging. Car manufacturers aiming at the reduction of vehicle weight replace steel parts with aluminium, plastics, and composites. It is forecast that in the near future polymers and polymer composites will account for about 20% of vehicle weight. Car makers are also introducing materials containing natural fibers in order to economize in the manufacturing and on the weight of vehicles. Fiat and Daimler–Chrysler, for example, use linen and hemp fiber to make some selected car parts such as engine guards. In India, jute fiber is primarily used to produce composites. When combined with a polyester matrix, the mixture can be used to produce pipes, molds, slabs, and panels. The Indian government promotes large projects related to the use of jute fiber in the construction industry [7]. It is estimated that in the USA the demand for natural fiber in the automobile industry will rise annually by 30% and that in the construction sector by as much as 60% [9].

In recent years a new generation of biocomposites, made of biodegradable polymers as the matrix and natural fibers as strengthening components, has been emerging. Despite higher costs of manufacture, these materials should eventually compete with traditional composites because of their degradability. It is estimated that the increase in sales of biocomposite products will rise by 20–30% annually. What is more, the use of different biopolymer mixes with cheaper plastics may enable a balance between cost and biodegradability to be achieved. The trend is to replace traditional polymers as much as possible with biodegradable materials displaying high stability when used and having no negative effect on environment after their life cycle [9, 13–15].

The most common fibers in biocomposites come from linen, hemp, cotton, jute, coconut, banana, and leaves of various kinds of agave. The basic problem with the proper application of natural fibers is their great variation in quality and mechanical properties. Synthetic fibers such as glass fiber and carbon fiber have very specific physical characteristics, but the features of natural fiber depend on many factors, such as their origin, the age of the plant, whether the material comes from leaves or stem, and on the process of obtaining the fiber and its preparation.

Natural fibers should be subject to certain preparatory operations and modifications of their surface. After this process, they should display the following features:

- good adhesion between the fiber and matrix,
- suitable degree of polymerization and crystallization,
- resistance to humidity,
- non-inflammability, and
- homogenous physical properties.

## 10.6 Chemical Modification of Fibers

The chemical makeup and structure of a fiber depends on numerous factors such as climatic and cultivation conditions, age, and whether the fiber comes from leaves or stems. Natural fibers consist of more or less desirable components such as cellulose, hemicelluloses, pectin, lignin, wax, and water-dissolvable substances, all of which affect the fibers' physical characteristics.

***Cellulose*** is a natural, fibrous polysaccharide and a basic component of cell walls of higher plants as well as algae, fungi, and bacteria. Its molecule consists of 3000–14 000 linearly combined β-D-glucopyranose units joined through β-1-4-glucoside bonds. A disaccharide unit incorporated in cellulose is cellobiose. The extended linear structure and numerous hydrogen bonds between glucose molecules create the opportunity for the development of the structures known as fibrils. In their vicinity, crystal structures of cellulose, the so-called micelles, are created. These are bordered by amorphous cellulose and free inter-micelle zones. The β bond contributes to the development of long, rigid threads of molecular weights of ca. 570 000. The highest cellulose content is found in cotton fibers [16, 17].

The results in Table 10.1 show considerable differences in the chemical makeup of different fibers. The lowest cellulose content and highest lignin content is observed in coconut fiber. The quantity of lignin and cellulose depends in the first place on the age and species of plants that provided the fiber [9].

***Hemicellulose*** is a hydrophilic polymer; it therefore largely determines the water absorption by vegetable fibers [6].

***Waxes*** influence the quality of fiber-polymer bond and hence the durability of obtained composite.

Both the quality and the properties of fibers depend on their length, size, maturity, and methods of processing. Table 10.2 compares the mechanical characteristics of selected natural fibers and synthetic fibers.

**Table 10.1** Chemical compositions and structural parameters of some fibers [18].

| Types of fiber | Cellulose | Lignin | Hemicellulose | Pectin | Wax | Microfibrillar/ spiral angle (Deg.) | Moisture content |
|---|---|---|---|---|---|---|---|
| jute (*Corchorus capsularis*) | 61–71.5 | 12–13 | 13.6–20.4 | 0.2 | 0.5 | 8.0 | 12.6 |
| flax (*Linum usitatissimum*) | 71 | 2.2 | 18.6–20.6 | 2.3 | 1.7 | 10.0 | 10 |
| hemp (*Cannabis sativa*) | 70.2–74.4 | 3.7–5.7 | 17.9–22.4 | 0.9 | 0.8 | 6.2 | 10.8 |
| ramie (*Boehmeria nivea*) | 68.6–76.2 | 0.6–0.7 | 13.1–16.7 | 1.9 | 0.3 | 7.5 | 8.0 |
| kenafu (*Hibiscus cannabinus*) | 31–39 | 15–19 | 21.5 | – | – | – | – |
| sisal (*Agave sisalana*) | 67–78 | 8.0–11.0 | 10.0–14.2 | 10 | 2.0 | 20.0 | 11.0 |
| henequen (*Agave fourcroydes*) | 77.6 | 13.1 | 4–8 | – | – | 14.0 | – |
| cotton (*Gossypium* L.) | 82.7 | – | 5.7 | – | 0.6 | – | – |
| coir | 36–43 | 41–45 | 0.15–0.25 | 3–4 | – | 41–45 | 8.0 |

**Table 10.2** Comparative properties of some natural fibers and conventional man-made fibers [9].

| Types of fiber | Density ($g\,cm^{-3}$) | Diameter ($\mu m$) | Tensile strength (MPa) | Young's modulus (GPa) | Elongation at break (%) |
|---|---|---|---|---|---|
| jute (*Corchorus capsularis*) | 1.3–1.45 | 25–200 | 393–773 | 13–26.5 | 1.16–1.5 |
| flax (*Linum usitatissimum*) | 1.50 | – | 345–1100 | 27.6 | 2.7–3.2 |
| hemp (*Cannabis sativa*) | – | – | 690 | – | 1.6 |
| ramie (*Boehmeria nivea*) | 1.50 | – | 400–938 | 61.4–128 | 1.2–3.8 |
| sisal (*Agave sisalana*) | 1.45 | 50–20 | 468–640 | 9.4–22.0 | 3–7 |
| cotton (*Gossypium* L.) | 1.5–1.6 | – | 287–800 | 5.5–12.6 | 7.0–8.0 |
| coir | 1.15 | 100–450 | 131–175 | 4–6 | 15–40 |
| E-glass | 2.5 | – | 2000–3500 | 70 | 2.5 |
| S-glass | 2.5 | – | 4570 | 86 | 2.8 |
| aramid | 1.4 | – | 3000–3150 | 63–67 | 3.3–3.7 |
| carbon | 1.7 | – | 4000 | 230–240 | 1.4–1.8 |

Properties such as density, lack of electric conductivity, maximum tension, etc. depend on the internal structure and chemical makeup of fibers. Durability and rigidity is strictly related to the angle between the axis and fibril of the fiber. If the angle is smaller, the durability is better. Coconut fibers display the lowest durability (Table 10.2). They contain little cellulose and have a large fibril twisting angle (Table 10.1). On the other hand, the high level of maximum tension of linen fibers may be connected to high cellulose content and a relatively small twisting angle of microfibrils (Table 10.1). Some mechanical properties of natural fiber (durability, elasticity, rigidity) can be comparable to those of glass fiber. In some cases,

natural fiber shows better parameters than glass fiber; hemp fibers, for example, are more rigid.

Both in the designing stage of a biocomposite and during its application, natural fibers have to be selected for the best mechanical properties combined with good processability. Low thermal resistances of natural fibers can cause many problems in the selection of polymers as matrix material. The processing temperature should not exceed 200 °C for more than 10 minutes. Higher temperatures and longer process times may result in weakening of the fiber and as a result the sturdiness of the composite. Fibers possess different thermal durabilities; ramie fiber, for example, loses 10% of its tear resistance after 10 minutes at a production temperature of 200 °C [18].

## References


**1** Pielichowski, J. and Puszyński, A. (1998) *Technologia tworzyw sztucznych* (in Polish), WNT, Warszawa.

**2** Johannaber, F. (1999) *Przetwórstwo tworzyw sztucznych* (in Polish), Plastech WPiKT, Warszawa.

**3** Sikora, R. (1993) *Przetwórstwo tworzyw wieloczasteczkowych* (in Polish), Wydawnictwo Zak, Warszawa.

**4** Małaśnicka, W. and Małaśnicki, J. (1972) *Technologia tworzyw sztucznych cz. II* (in Polish) WSiP, Warszawa.

**5** Avérous, L., Fringant, C. and Moro, L. (2001) Starch–based biodegradable materials suitable for thermoforming packaging. *Starch*, **53**, 368.

**6** Baley, C. (2002) Analysis of flax fibres tensile behaviour and analysis of the tensile stiffness increase. *Composites: Part A*, **33**, 939.

**7** Bledzki, A.K. and Gassan, J. (1999) Composites reinforced with cellulose based fibres. *Progress in Polymer Science*, **24**, 221.

**8** De Carvalho, A.J.F., Curvelo, A.A.S. and Agnelli, J.A.M. (2001) A first insight on composites of thermoplastic starch and kaolin. *Carbohydrate Polymers*, **45**, 189.

**9** Mohanty, A.K., Misra, M. and Drzal, L.T. (2001) Surface modifications of natural fibers and performance of the resulting biocomposites: an overview. *Composite Interfaces*, **7**, 313.

**10** Mościcki, L., Janssen, L.P.B.M., Mitrus, M., Oniszczuk, T., Rejak, A. and Juśko, S. (2007) Baro-thermal techniques in processing of thermoplastic starch. *Acta Agrophysica*, **9** (**2**), 431–42.

**11** Stamboulis, A., Baillie, C.A. and Peijs, T. (2000) Effects of environmental conditions on mechanical and physical properties of flax fibers. *Composites Part A: Applied Science and Manufacturing*, **32**, 1105–15.

**12** Zhang, M.Q., Rong, M.Z. and Lu, X. (2005) Fully biodegradable natural fiber composites from renewable resources: all-plant fiber composites. *Composites Science and Technology*, **65**, 2514–25.

**13** Mościcki, L., Janssen, L.P.B.M. and Mitrus, M. (2006) Przetwórstwo skrobi termoplastycznej na cele opakowaniowe (in Polish). *Inzynieria Rolnicza*, **6** (**81**), 65–72.

**14** Oniszczuk, T. (2006) Effect of parameters of injection moulding process on the structural properties of thermoplastic starch packaging materials. PhD Thesis. Lublin Agricultural University, Poland.

**15** Singleton, A.C.N., Baillie, C.A., Beaumont, P.W.R. and Peijs, T. (2003) On the mechanical properties, deformation and fracture of a natural fiber/recycled polymer composite. *Composites Part B: Engineering*, **34**, 519–26.

**16** Mitrus, M. (2004) Wpływ obróbki barotermicznej na zmiany właściwości fizycznych biodegradowalnych biopolimerów skrobiowych. PhD thesis (in Polish). Akademia Rolnicza w Lublinie, Poland.

**17** Sinha Ray, S. and Bousmina, M. (2005) Biodegradable polymers and their layered silicate nanocomposites: in greening the 21st century materials world. *Progress in Materials Science*, **50**, 962–1079.

**18** Mohanty, A.K., Misra, M. and Hinrichsen, G. (2000) Biofibres, biodegradable polymers and biocomposites: an overview. *Macromolecular Materials and Engineering*, **276/277**, 1–24.

**19** Zawistowski, H. and Frenkler, D. (1984) *Konstrukcja form wtryskowych do tworzyw termoplastycznych* (in Polish), WNT, Warszawa.

**20** Zawistowski, H. (2000) *Technologie wtryskiwania, Jakośc i efektywnośc* (in Polish), Plastech WPiKT, Warszawa.